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Anne Lise RIAS, Frédéric SEGONDS, Carole BOUCHARD, Stéphane ABED - Towards additive manufacturing of intermediate objects (AMIO) for concepts generation - Towards additive manufacturing of intermediate objects (AMIO) for concepts generation p.1-15 - 2017

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Towards additive manufacturing of intermediate objects (AMIO) for concepts generation

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Abstract According to an analysis of existing Design For Additive Manufacturing (DFAM) methods, we first highlight that they present limits regarding product innovation. This paper then presents a creative approach to be integrated in the early stages of DFAM methods. Two case studies A and B are presented as the experimental application of the first stage of our creative approach. The results of these case studies highlight that designers need a new kind of Intermediate Representation (IR), especially to represent dynamic features. To address this need, we introduce the concept of AMIO Additive Manufacturing of Intermediate Objects. This new kind of IR is an expected output of the ideas generation stage. These intermediate objects are meant to be manipulated by all the design stakeholders, as an input for the concept generation stage, to enhance the generation of creative concepts for additive manufacturing.

Keywords Intermediate objects · Creative design · Creativity · Additive manufacturing · Design for additive manufacturing

1 Introduction

The main purpose of this paper is to highlight the need for a new kind of Intermediate Representation (IR) through a creative Design For Additive Manufacturing (DFAM) approach. We propose the new concept of Additive Manufacturing of Intermediate Objects (AMIO) as the new kind of IR. According to the recognized work of Teece [1], process innovations guide to product innovations. As Additive Manufacturing (AM) groups innovative manufacturing processes (i.e processes that enable to produce, by addition of material layer upon layer, a physical object from a digital file[1])., it has the potential to result in product innovations. Several authors advised that, to be successful, innovation should be guided through the steps of a design process [2]. To exploit the potential of AM for product innovation, several DFAM methods have been developed. The first section of this paper reports a classification of the early stages of existing methods regarding creative concepts generation. The classification highlights that product innovation opportunities are currently conditioned to the nature of the input data, to design strategies and consequently to the nature and the roles of the IRs. From these observations, Sect. 3 presents a framework of a creative approach to be integrated in the early stages of DFAM methods. This approach is first based on the use of a combination of two kind of inspirational examples: intra-domain examples and far-domain examples. Focusing on the definition of the required input data for a creative approach in DFAM, Sect. 4 reports two case studies (A and B). Case study A is focused on gathering intra-domain examples and case study B is focused on gathering far-domain examples, both for the project of Function integration. Through these two case studies, we emphasize the limits of conventional intermediate representations regarding a creative approach in DFAM. It raises the need of a

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[1] Definition from AFNOR NF E 67-001 Union de normalisation de la Mécanique, 2011 (french union for standardization in mechanics).

new kind of IR. In Sect. 5, we then introduce our concept of AMIO.

2 Research background: DFAM methods and creativity

2.1 DFAM methods principles

As the specific orientation of Design For X for the AM paradigm, DFAM groups methods that are intended to manage the required knowledge about product, process and material as soon as the product lifecycle starts. Theses stages correspond to the so-called early stages of the design process [3]. Conducting a review of existing DFAM methods, Laverne et al. [4] asserts that there are 3 types of DFAM methods.

Type 1: Opportunistic DFAM methods. They guide designers to take into account AM specificities, such as the geometrical and material distribution freedoms, from the beginning and during the design process. These methods lead to the creation of IRs [5,6]. Some representations are created by the designer for him/herself in a reflexive practice, and some are intended to be shared with the design stakeholders [7]. Intermediate Representations embody different types of design and technical information all along the stages of the design process. Thus, IRs are of different natures: sketches, drawings, models and prototypes [8].

Type 2: Restrictive methods consider AM limits and define criteria, such as manufacturability and cost, to evaluate the IRs regarding AM specificities [9,10]. They guide designers to progress from ideal IRs to realistic ones, by embodying the variations due to the manufacturing constraints.

Type 3: Dual DFAM groups methods combining the two previous approaches. Laverne et al. assert that they are more suitable for product innovation since it guides designers to exploit AM potential in a realistic way. Indeed, by conducting both IR creation and IR evaluation during the early stages, these methods help avoiding late design changes which cause extra cost and longer development time.

2.2 Impacts of input data and design strategies on generated concepts qualities

Based on the cited categorization, we analyzed Dual DFAM methods by focusing on the required input data and the qualities of the concepts they guide to generate [11]. The analysis is represented through a 3 levels classification: 1/ Formal newness 2/ Functional reconfiguration 3/ AM Form & Function implementation. These 3 levels represent the 3 different existing strategies to process from the input data to the generated concepts. A product can be generally described by its features i.e its main functions and forms, where function means what the product does and form how it is accomplished. Form means any aspect of physical properties: shape, geometry, construction, material or dimensions. There may be several forms to achieve a single function [12]. Some authors use the terms of inner and outer features [13] or internal and external features [14] to distinguish which forms and functions define the product boundaries from those that are not situated at the interface with the products environment or with other components in case of an assembly.

Table 1 below synthesizes the comparison between the 3 design strategies and the generated concepts qualities. The analysis shows that Dual DFAM methods guide designers to generate concepts that are only partially new (a maximum of 75% of newness), while creative concepts are suitable for a more radical innovation than architectural innovation [2]. Concepts qualities are defined according to the criteria of Garcia et al. [15] which specify that newness should be evaluated from both the perspectives of what is new and who it is new to. Based on the definition of Bonnardel et al. [16], we define that, in our study, creative concepts are concepts that present:

1. New features: never realized in conventional industry nor the AM industry,
2. Realistic features: feasible with AM processes,
3. Useful features: presenting values for at least one of the targeted industrial sectors.

Level 1: Formal newness This category groups the methods from [17–22]. They are oriented to the redesign of existing products. As shown in Fig. 1 below (left column), the used input data refers to the existing product inner and outer forms, inner and outer functions as well as assembly constraints. The purpose is to redesign in order to make the product suitable and optimized for AM.

Oriented towards optimization techniques in downstream stages (such as topological optimization i.e the material repartition to achieve a desired function for a given set of loads and constraints [23]), these methods use analogical reasoning from various examples of lightweight and resistant natural structures like bones, crystals or cells to generate AM lattice structures. This bionic approach leads to new forms which can be produced only by AM. However, these methods do not include a functional analysis. Indeed, products functions are considered as fixed input data, they are not questioned regarding AM capabilities. These methods finally guide to concepts that can be realistic but only partially new: their forms are new regarding the existing product which is redesigned but their functions are not (Table 1 below, left column).

Level 2: Functional reconfiguration Methods of this category are from Munguia et al., Rodrigue et al. and Boyard et al

Table 1 Summary table comparing the DFAM strategies and their generated concepts qualities of the 3 identified levels (O = No newness, X = Newness)

Generated concepts qualities	Level 1: formal newness	Level 2: functional reconfiguration	Level 3: AM F & F implementation
New what			
Functions (25%)	O	O	X
Forms (25%)	X	X	X
New to			
AM industry (25%)	X	O	O
Conventional industry (25%)	X	O	X
Level of newness allowed by the methods (max. 100%)	75%	25%	75%
Realistic to AM capabilities	Yes	Undefined	Yes

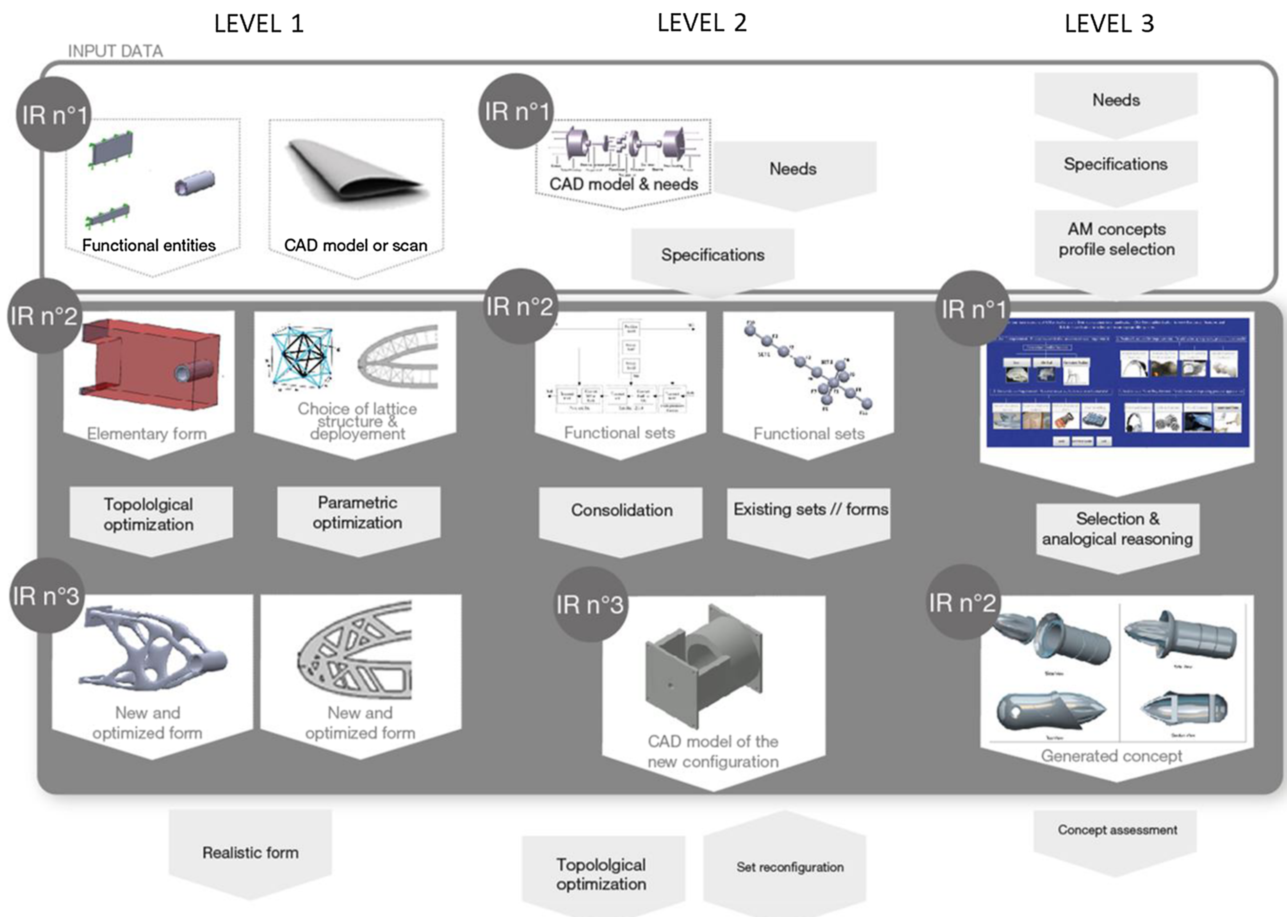

Fig. 1 Intermediate representations created during early stages of Dual DFAM methods, based on [13,14,18,21,25]

[13,24,25]. They are dedicated to redesign existing products that embody assemblies, or in other words to define relations between multiple components. The purpose is to consolidate i.e to reduce the number of components of existing assemblies [13] or of existing whole products [24]. Case-based reasoning is used to define components features, applied from a database of precedents i.e previously designed artefacts showing solutions that are not specific to AM. A creative tool based on TRIZ is used in downstream stages, when features are already defined, to target which of them can be optimized. Finally, these methods do not ensure manufacturability. They guide to the generation of concepts that may be useful but not new regarding conventional industry nor the AM industry. The feasibility of the generated concepts is not evaluated then the criteria Realistic is considered as undefined (see center column on Table 1 above).

Level 3: AM Form and Function implementation The DFAM methods of Burton et al. [26] and Maidin et al. [14] are intended both to the design or redesign of products. Their purpose is to globally emphasize the use of AM in product design. First, a concept profile selection based on a questionnaire [27] opens to a case base of AM existing features. Analogical reasoning from precedents is used to define rather components or whole products, and both at their functional and formal levels. In this case the considered precedents are specific to AM as shown in the extract Fig. 2. These methods guide designers to the generation of concepts which can be new regarding existing conventional products and realistic regarding AM capabilities. However, by using only AM precedents, they condition creative opportunities without looking for new solutions. Moreover, restricting designers to some existing AM solutions seems to be a weak approach since current AM background is quite reduced, due to the relative newness of AM processes compared to conventional processes [21]. Technical surveys also show that this background is also expanding along to AM improvements [28].

2.3 The intermediate representations sequence in Dual DFAM early stages

The previous section emphasized that input data and design strategies strongly impact the qualities of the generated concepts. Indeed, using only examples of existing features as sources of inspiration condition designers to generate only partially new concepts. The input data and design strategies applied in Dual DFAM methods also impact the nature and the role of the IRs. It is generally recognized that in early stages, designers bounce from IR to IR to extend their ideas, from fuzzy ones to more detailed concepts [7,29]. In this sense, the characteristics of the created representations influence both designers strategies to generate concepts and the concepts qualities. In Fig. 1 (see above), we compare the characteristics of the IRs created within the early stages of the 3 levels Dual DFAM methods.

Firstly, it is easily noticeable that 3D modelling plays a key role. Indeed, it is used as soon as the first step in Levels 1 and 2 methods and all along the early stages of all the methods. 3D modelling is both part of the design strategies and a tool to represent the concepts. All methods result in 3D virtual models (in Fig. 1 represented by renderings and screenshots). This leading role of 3D modelling is consistent with the digital sequence of AM which has to result in a 3d model out of STL or AMF format in order to process to AM. Analyzing the IRs, we observe that the uses of 3D modelling influences positively and negatively their nature and their roles, and thus impacting the generated concepts qualities. The main observation is that in all the Levels 1, 2 and 3 methods concepts are represented only virtually and not physically embodied. It presents the great advantage to keep the concepts editable (more or less easily, depending on the software). Yet, AM is now often recognized as manufacturing tools simple enough to allow to rapidly obtain physical artifacts. The work of Oxman [30] and Sass [31] emphasized the power of AM not only to prototype in downstream stages but as a digital tool that pushes to consider the early stages as the definition of interactive, dynamic and responsive designs.

Level 1 methods are strongly oriented by generative 3D modelling. It is no doubt that the IRs n^{o}3 (see Fig. 1 above) could have been different if modelled with a conventional CAD approach. In one hand, generative modelling supports designers in representing complex and/or new geometries without limiting them to their own skills and imagination. In the other hand, we also notice that it rapidly converges to a single concept, represented by a single 3D virtual model that is closed i.e not intended to be easily editable except in a range of predefined settings. Rapid convergence without a divergent stage of exploring the solution space is not suitable for creative design.

In Ponche et al. [21] the concept is abstracted to show only its required functional entities (IR n^{o}1 on Fig. 1) i.e the outer features that cannot be modified. In addition, a bounding box is also modelled. It represents the maximal geometrical volume wherein the concept can be defined. The resulting IR n^{o}2 is then called *Elementary form* (see Fig. 1 on the left). At this point, the concepts functions are fixed while the form is still undefined. In the other methods of Level 1, existing 3D scans or CAD models of a product are used as input data. In this sense, the concept IR n^{o}1 is preexisting. It is not abstracted but already detailed. Designers possibilities to edit the 3D virtual models then depends on the model file format. If it is editable, the representation can be augmented with new features. For example, in Fig. 1 right side of Level 1, the 3D virtual model is augmented with an internal lattice structure. If it is not editable, designers have to remodel it. Actually, the forms will not be 3D modelled by designers but automatically generated by a software through a topological optimization approach. They are generated according to settings such as load cases, material, center of gravity and others. In practice, available softwares for topological optimization such as Inspire or Optistruct do not yet allow the integration of every settings. For instance, they can generate forms that are not feasible with AM. Further iterations on 3D models in downstream stages are then required, especially in order to build a model that can be manufactured. Considering this technical lack, the generated IRs n^{o}3 are to be considered more as suggestions than as models to be used to manufacture. In Ponche et al. [21] creation of IR n^{o}3 is entirely supported by generative modelling while in Maheshwaraa et al. [18], IR n^{o}3 is a hybridization between a preexisting representation (the outer features) and an automatically generated new representation (the inner features).

Level 2 methods are based on preexisting models of products (IR n^{o}1 on Fig. 1). These representations are abstracted under the form of Functional sets. The product itself become invisible but represented by diagrams of the relations between its features (IR n^{o}2 on Fig. 1 Level 2). Thereby, product features can be questioned and modified without spending time nor effort on 3D modelling at this phase. It facilitates the exploration of multiple concepts. By not requiring any skill in 3D modelling, the functional sets also foster collaboration between experts of heterogeneous knowledge and skills. Collaborative approaches are recognized as suitable for concept generation especially to generate useful concepts [32]. Nevertheless, the digital sequence is not broken. It is kept consistent since preexisting 3D virtual models are stored in a database behind functional sets. These 3D models are design solutions that have been downloaded or modelled during previous design projects. Designers can then pick up models from databases similar to the concept to be generated. The resulting IR n^{o}3 is a hybridization from several preexisting 3D virtual models composed in a new configuration. This configuration is later submitted to a software for topological optimization in downstream stages.

However, we point out three negative influences of the use of preexisting 3D models regarding newness and realism criteria. Firstly, functional sets are not intended to the addition of new features but to the reconfiguration of existing ones. The preexisting 3D virtual models to be reused don't guide designers to the generation of new features. Secondly, even if Level 2 methods are specifically oriented to assemblies and whole products, the created IRs are static models while functional concepts have at least two different states of being (On/Off) and can present several behaviors. Renderings and screenshots are static representations that dont allow to experiment actionable features. Thirdly, the databases group 3D virtual models that are not specific to AM [25]. In other words, designers are not guided to generate concepts which are feasible in AM and the IRs dont show the level of realism of the generated concept.

In Level 3 methods designers are first nourished with a taxonomy of preexisting products representations. This case base shows AM features illustrated by pictures zooming on some existing products and by associated keywords (see Fig. 2 below).

In a similar way to the databases of Level 2 methods, the taxonomy helps designers to rapidly obtain a first representation of the concepts features and to iterate on it without spending time nor effort in 3D modelling. Moreover, browsing through the cases base allows to explore multiple design solutions. So here, this taxonomy plays both the roles of input data and IR n^{o}1 (see Fig. 1). However, we note some negative influence regarding AM creative concepts generation. The taxonomy presents pictures of AM products and keywords, it does not allow to directly view and/or download 3D virtual models. It does not allow either to interact with a physical version of the showed products examples. 3D modelling steps in later than in Levels 1 and 2 methods. In this sense, the AM digital sequence is broken. How are designers supported if they want to generate a concept with features similar to one of the taxonomy? Do they have to model it from scratch even if it is time and resources consuming? The resulting IR n^{o}2 (see Fig. 1 on the right) created to show one or more concepts is composed of renderings from different points of view but again, these static representations dont allow designers to experiment the different concepts states of being and behaviors. Through this analysis, we retain that a suitable IR sequence for creative AM concepts generation would provide to designers preexisting 3D virtual models and would allow designers to experiment dynamic concepts and behaviors. The 3D virtual models would not exactly represent existing products but present noticeable AM features.

3 Integration of a creative approach in early stages of DFAM

The previous sect. 2.2 highlighted the impact of the input data and of the design strategies on the qualities of the generated concepts. Section 2.3 emphasized the influences of 3D modelling on the IRs characteristics. We then assume that there are 3 action levers to enhance the generation of creative concepts in early stages of DFAM: 1/ Define the nature of the input data to be used, 2/ Foster divergence and exploration in the design strategy and 3/ Guide the IRs creation. To act on these levers, we propose a framework of a creative approach. This approach is to be integrated in early stages of Dual DFAM methods. We then present two case studies (A and B) conducted specifically on the action lever 1. The results highlight the need for a new kind of IR, especially to represent dynamic features.

3.1 Framework of the proposed creative approach

Figure 3 below presents a framework for our creative approach in 5 stages. It is rooted in Maidin [14] and Boyard [25] DFAM methods. It can be applied by all design stakeholders who already have some knowledge about AM processes. It is intended to impulse R&D collaborations between designers and industrial partners interested in emphasizing the use of AM in the industrial sector they work for.

Creative designers use sources of inspiration as input data in order to stimulate their ideas production. They gather visual and textual information to get inspiration about features that could be, by analogical or case-based reasoning, implemented in the concept to be designed [33–36]. In the same way, they also use precedents. By being examples of existing solutions, artifacts, graphical and textual informa-

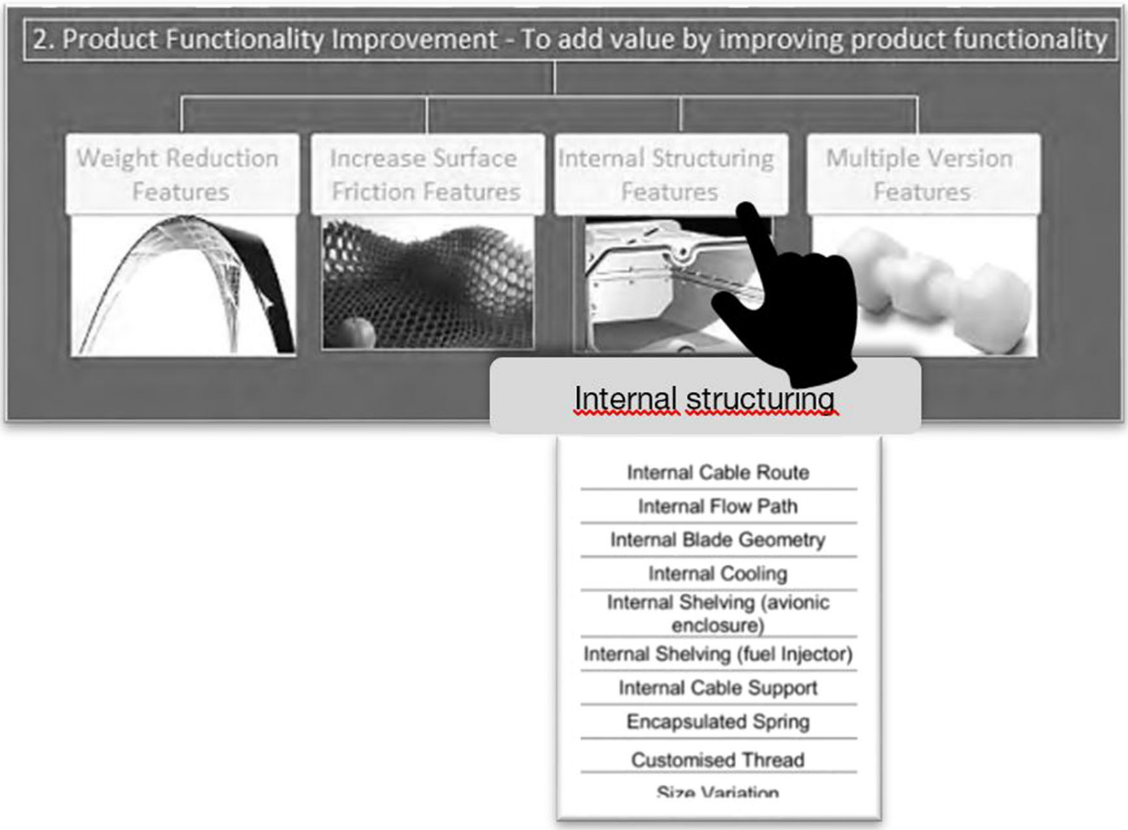

Fig. 2 Extract from the taxonomy of existing examples represented by pictures and keywords [14]

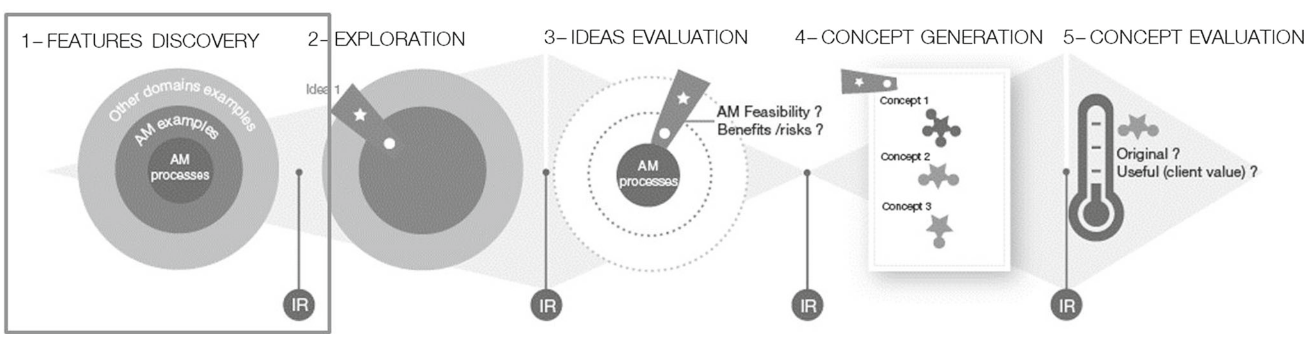

Fig. 3 Proposed framework of a creative approach for early stages of DFAM

tion embody design knowledge which activates the designers personal knowledge. Recently activated knowledge by precedents is used to generate ideas [37]. According to Bonnardel et al. [38] inspirational examples can be found within the concept domain (i.e *intra-domain*), here AM products background. They also can be found far from these domains (i.e *far-domain* examples). DFAM methods of Levels 2 and 3 show that being inspired only by *intra-domain* examples leads to partially creative concepts. Level 1 methods show that being inspired only by *far-domain* sources (bionic inspiration in these methods) also guide to partially creative concepts. Therefore, we assume that the first stage of our framework must guide the design team to gather a corpus of both *intra-domain* examples and *far-domain* examples to be combined and used as input data of the creative process.

1/ Features Discovery (Fig. 3 stage 1) The first task for designers is to gather examples of AM products (i.e features already realized in AM) and *far-domain* examples (i.e features not yet realized in AM). The purpose is to have a great view of what has been done and what can still be created. The survey should be regularly enriched according to

AM developments. The expected IR is a taxonomy showing on one side 3D virtual editable models and associated keywords as abstractions of preexisting AM products and, on the other side, pictures & keywords representing far-domain examples.

2/ Exploration (Fig. 3 stage 2) This stage consists in randomly and systematically combining an AM example to a far-domain example in order to generate ideas. At least one idea should be formulated for each combination. The expected IRs at this stage should show edited 3D virtual models embodying the generated ideas. As output of this stage, designers should have a portfolio of various and numerous ideas that present potential opportunities for the development of new concepts.

3/ Ideas evaluation (Fig. 3 stage 3) A first idea evaluation is conducted by AM experts. The generated ideas are faced to AM processes in order to scale the ideas at a mature level i.e they are feasible with current AM processes or an emergent level i.e potentially feasible if AM processes improve. The expected IRs should be 3D virtual models that can be manufactured with AM. The proof of the ideas feasibility is established by actually manufacturing them. This stage should result in a reduced portfolio of ideas embodied in artifacts which can be manipulated.

4/ Concept generation (Fig. 3 stage 4) This stage is conducted by designers in a collaborative approach with industrial stakeholders in order to enhance the generation of concepts with a high client value. The artifacts should stimulate design team in analogical reasoning in order to translate the previous ideas into concepts. The expected IRs should be scenarios showing industrial potential applications of the concepts.

5/ Concept evaluation (Fig. 3 stage 5) The purpose is to identify the concepts to be further detailed and optimized in downstream DFAM stages. The required profiles for the evaluation are experts of AM who have a good understanding of industrial sectors where AM is integrated, such as innovation managers, senior designers and trade engineers for example. They are asked to say how much the generated concepts are: New regarding traditional products of the involved industrial sector and regarding AM industry, Useful regarding the involved industrial sector (client value), Realistic regarding AM capacities.

4 Features discovery in DFAM: case studies

4.1 Background and purpose: function integration

The industrial application case of our framework is the generation of new concepts of industrial metal parts exploiting one of the AM specificities: the functional complexity [17,39]. Indeed, AM processes allow designers to access to the internal volume of products in order to integrate within the parts one or several additional functions. This application of our proposed creative approach is based on a technical survey. Researches of Cham [40], Kataria [41] and De Laurentis [42] show that it is technically possible to embed bearings, nuts, screws and gears in products during their fabrication. Following works of Li [43], Lopes [44] and Chen [45] demonstrate the inclusion of sensors, magnets and some electronic components, supplemented by works of Isanaka [46], Panesar [47] and Wu [48]. The developed case studies A and B focus on the first stage of the framework: FEATURES DISCOVERY (the framed stage on Fig. 3 above) when intra-domain and far-domain examples are gathered to be input data of the creative process. They have been conducted separately with different participants and in different periods of time.

4.2 Case study A: gathering intra-domain examples

Case study A is rooted in the work of Maidin [14] that present a DFAM features database extracted from pictures showing existing AM products and designers answers to a survey. However, it was more oriented to consumer products, rather than industrial metal parts. Then, some categories such as *Aesthetics* or *User fit* were not consistent with our industrial research context. Moreover, according to the rapid improvements of AM processes the database needs to be updated. The goal of case study A is to identify what are the typical features of AM industrial metal parts.

4.2.1 Protocol

Participants A population of 22 novice designers with basic knowledge about AM participated. 4 experts in design science conducted the analysis of the phrased terms.

Tasks, duration and expected outcomes Each participant was asked to fill in an online survey with his/her own keywords to describe functional and formal characteristics particularly noticeable in a given series of 4 pictures. The characteristics could be inner or outer features. A 2 min oral brief introduced the task which was then done during 30 min for each participant. They were first asked to phrase noticeable formal characteristics and secondly asked about the functional characteristics. It was specified that only adjectives and/or nouns were expected for formal characteristics and only verbs for functions. 3 keywords per picture were asked about forms and 3 keywords about functions. In order to keep the digital chain consistent as recommended in DFAM. The expected IRs were 3D virtual

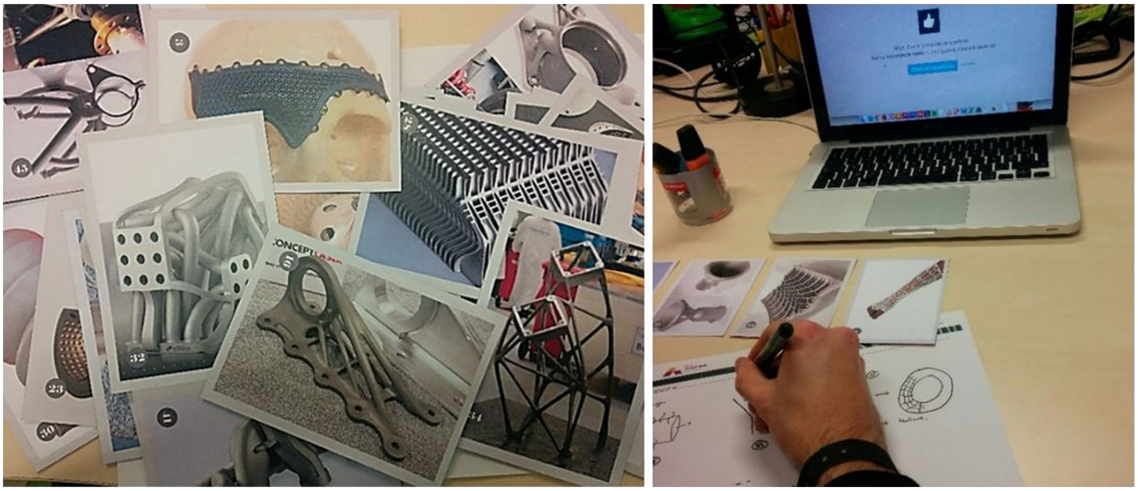

Fig. 4 The support tools used for case study A

models showing the phrased noticeable features. However, due to participants heterogeneous skills in 3D modelling, we had to minor the expected outcome. Consequently, they were asked to only sketch their keywords with conventional tools hand/paper/felt pen. Sketches allow to clear the meaning in case of participants difficulties to phrase and limit approximations in the interpretation during semantic analysis. 5 additional questions were submitted to participants and experts in order to evaluate their own performance regarding the tasks.

The device It is illustrated by Fig. 4 above. 51 pictures of AM products were selected as representative of seven industrial sectors: Aeronautics, Medical, Tooling, Space, Automotive, Robotics and Energy. These sectors are considered representative of the integration of AM in industry [28] and consistent with the business sectors of the industrial company context of our research. The series of 4 pictures were randomly constituted but checked in order to represent 4 different industrial sectors each.

Evaluation method According to Maidin [14], functions and forms may be common to several industrial sectors. Then a qualitative analysis (semantic proximity), was applied by the experts to group the terms under taxons and label the clusters instead of grouping them according to industrial sectors. According to Ullman [12], parts may be described by the relation between function and form they embody. The survey was then formatted to keep coupled the functional and formal characteristics that participants phrased at the same time. A quantitative analysis has been applied to evaluate the occurrence frequency of the couples. The typicality is defined according to the result of the quantitative analysis.

4.2.2 Results

242 formal characteristics have been phrased by participants. The experts grouped these terms under 31 different taxons according to the meaning of the keywords. Terms with similar meaning have been categorized under the same taxon. At the same time, 251 functional characteristics have been phrased by participants. The experts grouped them under 39 taxons. Table 2 below shows an extract of the taxonomy with the phrased forms grouped under the taxon COMPLEX TUBES and the phrased functions grouped under the taxon DRAW AND EXPEL During case study A, 383 different function/form couples have been phrased by the 22 participants. We conducted a quantitative analysis to identify which couples can be considered as typical of additive manufacturing features. Figure 5 below shows the results of the quantitative analysis. As showed on the figure, most of the couples (202) have been phrased only one time (left bar). Less than 1/3 of the couples (108) have been phrased twice. However, 9 couples have been phrased 5 times to 8 times by different participants. Indeed, 6 different couples have been phrased 5 times by the participants, 1 couple have been phrased 7 times and 2 couples have been phrased 8 times (see framed area on Fig. 5). We then deduce that the nine phrased couples can be considered as typical features of additive manufacturing through the mentioned 7 industrial sectors.

For example, Table 3 below presents two of these relevant couples. Couple 1 has been phrased 8 times and Couple 2 has been phrased 5 times. If presenting the detailed taxonomies would be of scientific and industrial interests, we retain that the main result of case study A is to be found in the semantic meaning of the terms. Most of the couples described dynamic features. For example, TO GUIDE A FLOW/BOTH CURVED AND PLANE. The semantic meaning induces an idea of a movement and an evolution within the same part.

Table 2 Extract of the taxonomy: forms grouped under the taxon "complex tubes" and functions grouped under the taxon "Draw and expel"

	FORMS		FUNCTIONS
COMPLEX TUBES	Interlaced tubes	Draw and expel	Drawing air
	Combined tubes		Repulse and attract a stream
	Concentric tubes		Bringing air
	Tangled tubes		
	Multi-output tubes		
	Dual duct		

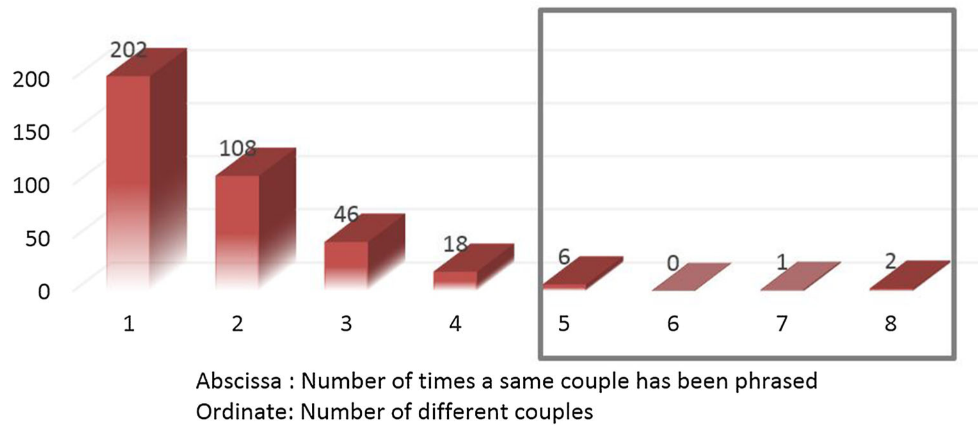

Fig. 5 Number of times form/function couples have been phrased

Table 3 Extract from our taxonomy of the typical features of additive manufacturing of industrial parts

COUPLE (nbr of times phrased)	FORM	FUNCTION
Couple 1 (8)	"CURVE AND STEEP"	"TO SLIM"
Couple 2 (5)	"EVOLVING FORMS"	"TO ASSEMBLE BY INSERTING"

Other couples mentioned two states at the same time: TO HEAT AND COOL/SKEW SURFACES.

Finally, the results of the performance evaluation survey highlighted that, according to 9 participants, finding keywords to express dynamic features is a pretty hard task because they are complex and intricate. 2 experts reported that 3D modelling intricate features is a pretty hard task especially when representing inner features.

4.3 Case study B: gathering far-domain examples

The goal of case study B is to gather far-domain examples in order to identify technical functions that could be integrated within metal parts in addition to typical industrial AM features.

4.3.1 Protocol

Participants 22 novice designers participated in case study B. They had basic knowledge about AM processes. Participants were asked to have skills in 3D modelling with any software. 3 AM experts were in charge of the evaluation of the generated data. Participants were sub-grouped by 3 and one group of 4.

Tasks, duration and expected outcomes (protocol illustrated by Fig. 6 below). A 30-min oral presentation started the experimentation to explain the context of function integration, the brief and the expected deliverables. The experimentation was composed of 6 successive sessions which lasted 2 h each. Each session was divided in 4 tasks. First, the groups were asked to phrase during 15 min some physical elements that could be included in AM metal parts, label them with keywords and grab pictures to illustrate them (see a/ in Fig. 6 below). The second task was a 20 min brainstorming session launched by a brief To include, incorporate, integrate a [one of the elements] in a volume, what effects does it produce? (see b/ in fig 6). The groups were asked to label the effects with one keyword and sketches (see c/ in fig 6). Thirdly, the groups had 10 min to select one of the effects among the ones

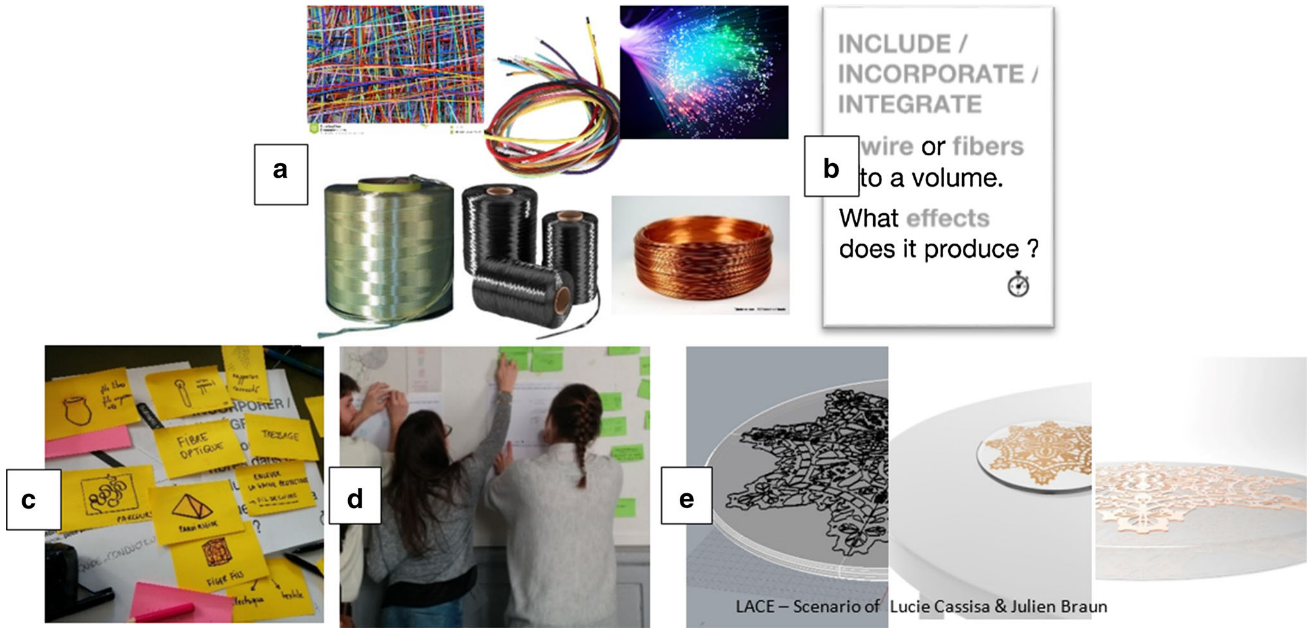

Fig. 6 The steps, input data and outcomes of the protocole conducted for case study B

phrased by the group seated next to them (part d/ in fig 6). Fourthly, the groups were asked during 1 h to generate at least one idea of a possible application of the function they just choose and 3D model it to explain the idea to the other groups under the template of a scenario with 3D virtual models and renderings (see e/ in fig 6). Session 1 was about the inclusion of solid elements, Session 2 on inclusion of liquids, the third one about wires & fibers (Fig. 6 illustrates that session), session 4 about electronic components, session 5 about powders and the last one about gas. A survey was finally submitted to participants in order to evaluate their own performance regarding the tasks.

Support tools Internet was available to grab pictures of elements. Reduced format of paper was given to guide participants to represent only simple sketches and few keywords instead of extended description during the brainstorming phase conducted at a sustained pace. 3D modelling was used at the final phase of the experimentation to represent the scenarios.

Evaluation method Afterwards, AM experts were asked to evaluate if the proposed functions were original regarding the technical survey (see sect. 4.1) and how well the proposed functional integration were in adequacy with the brief.

4.3.2 Results

40 different far-domain examples pictures have been grabbed by participants, representing 40 different elements that could be included in AM parts. The experts grouped them in 6 taxons according to their nature: solids, liquids, powders, wires and fibers, gas and electronic components. A total of 162 functions to be integrated in AM parts have be phrased by participants. AM experts evaluation eliminated the functions that were not adequate to the brief (such as aesthetic functions) and selected 79 relevant functions. A quantitative analysis allows to evaluate the potential of the phrased elements. Figure 7 below highlights that all elements have a great potential for the integration of new functions in AM parts, more than 10 functions have been phrased for every category. We notice that Gas have the greatest potential. Indeed, only 3 different gas have been mentioned by participants but they phrased that they can perform 11 different functions. Liquids and Powders also reveal a great potential, they can perform an average of 2,5 functions. We assume that there are, at least, as much potential concepts as the number of functions.

As in case study A, even if the exhaustive taxonomy of functions to be integrated in AM parts would be of scientific and industrial interest, the main result of this case study is to be found in the nature of the phrased functions and in the nature of the generated intermediate representations. More than the half of the phrased functions described dynamic features. Regarding the IRs, 18 participants choose, by their own initiative, to represent the dynamic functions under mini scenarios describing the different states or behaviors of the functions they had phrased (Fig. 8 below).

According to the performance survey results, 14 participants found that it was pretty difficult to accurately translate their application idea into a 3D virtual model. They said that

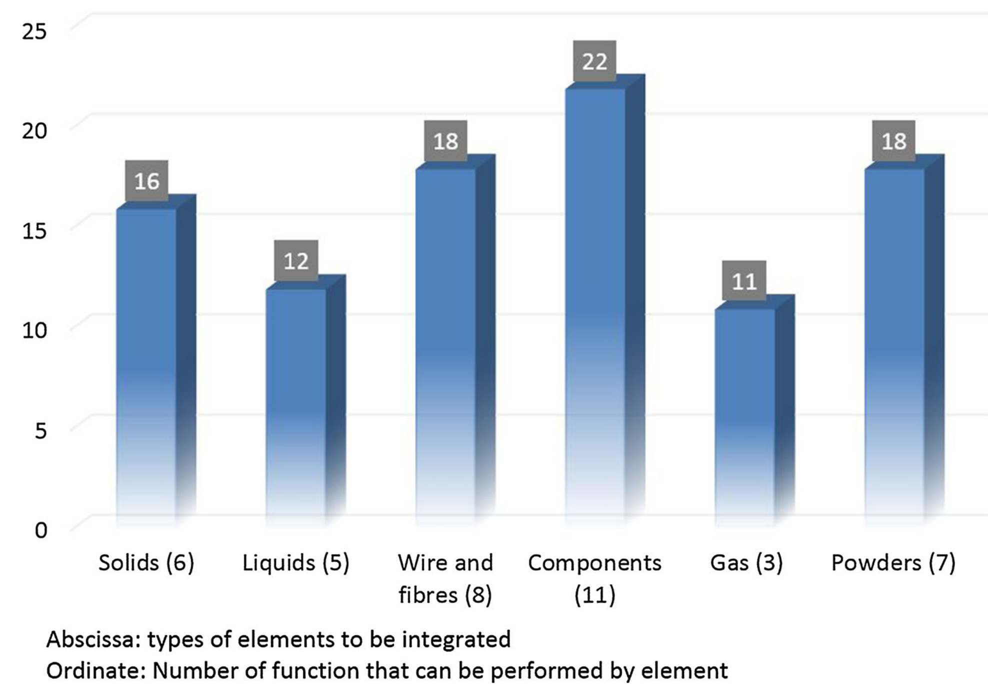

Fig. 7 Elements that can be included in AM parts and functions that can be performed

they had to simplify their intention. Moreover, 6 of them said they were not sure if the model would be functional if it would be actually manufactured.

4.4 Case studies A and B: discussion

Even if the two case studies were conducted separately, they have results in common. They both show that there is a gap between designers intentions and the information embodied in the created intermediate representations. It is especially true when designers want to represent complex features with inner and outer definitions and when it is about representing dynamic features. Participants have expressed the limits of keywords to describe evolving features while these ones are the most typical of AM. They also highlighted the limits of static representations while these ones show a great potential for product innovation in additive manufacturing. Through these results, the lack of interaction between designers and the representations appears. They also expressed the limits of their skills in 3D modelling while they wanted to experiment dynamic features and share their ideas within the groups. This gap raises the need for a new kind of intermediate representations in early stages of creative design for additive manufacturing. The intra-domain examples and far-domain examples gathered during case studies A and B constitute the input data to be used for the second phase of our framework: EXPLORATION. The application of this stage is beyond the scope of this paper.

5 Towards additive manufacturing of intermediate objects for creative concepts generation in DFAM

As demonstrated in case studies A and B, conventional intermediate representations media i.e sketched scenarios and 3D virtual models are not sufficient to accurately transmit designers intentions and to support them in the representation of functional complexity. Indeed, they dont allow designers team to represent and experiment AM concepts specificities as soon as the early stages, especially dynamic features. We then propose a definition of a new kind of intermediate representation, specifically oriented to creative design for additive manufacturing: Additive Manufacturing of Intermediate Objects (AMIO).

5.1 Background in interactive design

Interactive product design is a major economic and strategic issue in innovative products generation. In interactive design, the creation of a product is considered to be constrained by 3 factors: the experts' knowledge, the end-user satisfaction and the realization of functions [49].

To achieve these purposes, another part of interactive design research is focused on the digital chain supporting the processes. Indeed, the use of 3D virtual models as a kind of IRs created by design teams during a process is generally recognized and defined in interactive design [49]. Virtual models represent designers intentions and avoid interpretation in col-

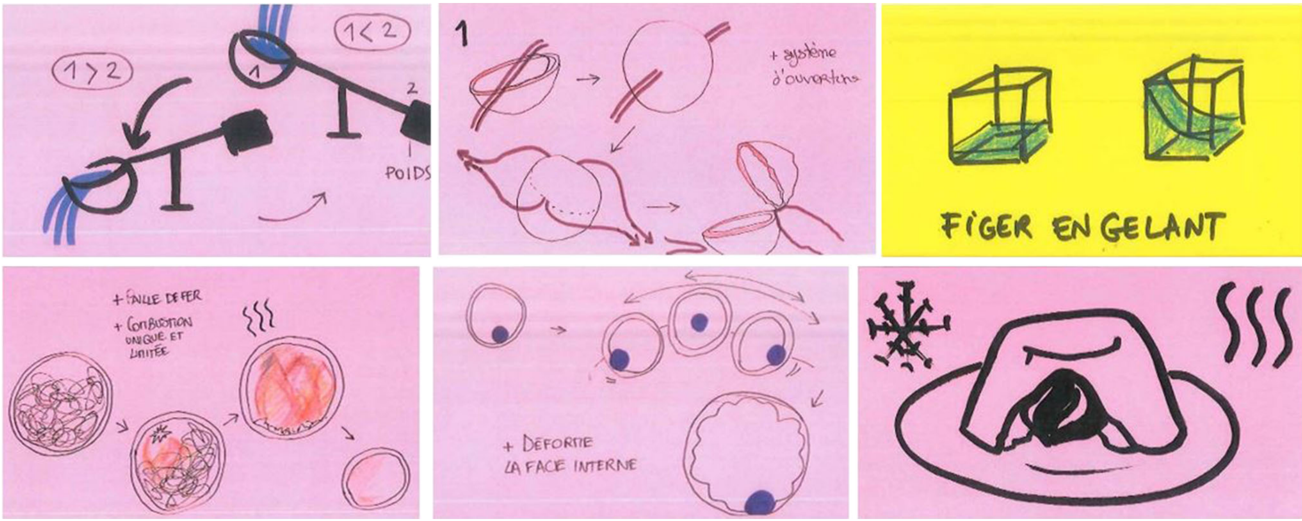

Fig. 8 Mini scenarios sketched by participants to represent dynamic features

laborative teams. Virtual simulation is also recognized as a medium for interactive design especially because it allows designers to virtually experiment and evaluate the concept to be designed.

To achieved these purposes, a part of interactive design research is focused on iterative loop processes and on agile methods [50]. Some of these researches are particularly focused on 3D physical models as a kind of IR and recognize them as experience triggers that allow design stakeholders to feel material, shape, surface texture, sensations, sonority, weight and others sensitive aspects [51]. Based on previous researches, Boujut [52] introduced the concept of "Intermediate Objects" to label these experience triggers used in interactive creative design.

Research work of Cruz et al. [53] specified the role of Intermediate Objects in early stages of creative design with the notion of *Open-ended* objects in opposition to *Closed* objects. Indeed, physical objects such as mock-ups and prototypes are often used by designer teams to validate some design solutions. These objects are not intended to be modified, they are then considered closed. On the contrary, *Open-ended* objects are made to be indefinitely modified because they are not meant to embody design solutions. They have four main purposes:

- They create a shared experience in the beginning of creative design processes that will infuse in designers minds during creative sessions,
- They are not exactly objects since they should be quite abstract, minimalist and simple,
- They should be functional so designers can observe, try and feel,
- Finally, they are a tangible translation of the brainstorming brief.

In other words, *open-ended* objects are media to explore the brief through experience rather than through language. In this sense, they are meant to be useful in multidisciplinary design teams. This background in interactive design echoes two characteristics of additive manufacturing. Indeed, additive manufacturing requires a 3D file as input data. Consequently, DFAM stages are crossed by a digital chain which support designers to bounce from 3D virtual representations to a final 3D file gathering the required data for manufacturing. Secondly, AM processes enable the embodiment of concepts into tangible versions (i.e a kind of object) as soon as the early stages of the design process. In other words, AM questions the conventional interactive design approach based on feature-based modelling [54]. We propose to add the stage of early manufacturing of AMIO.

5.2 Conceptual definition of AMIO

According to that background, we propose a conceptual definition of AMIO in creative design for additive manufacturing. AMIO are meant to be at the crossing point between closed and open-ended objects. Figure 9 below shows that AMIO are part of the intermediate representation sequence illustrated by an example of the generation of a new function for turbine blades.

We assume that AMIO could foster the generation of AM creative concepts as it can play the role of a mediation to ease the collaboration between AM designers and industrial stakeholders from several industrial sectors.

As additive manufacturing processes need 3D virtual model as input data, the AMIO can be easily manufactured from the IR n^{o}2. AMIO thus create a link between a virtual experience of an idea and a tangible experience of it: they are easily manually actionable (see IR n^{o}3 on Fig. 9).

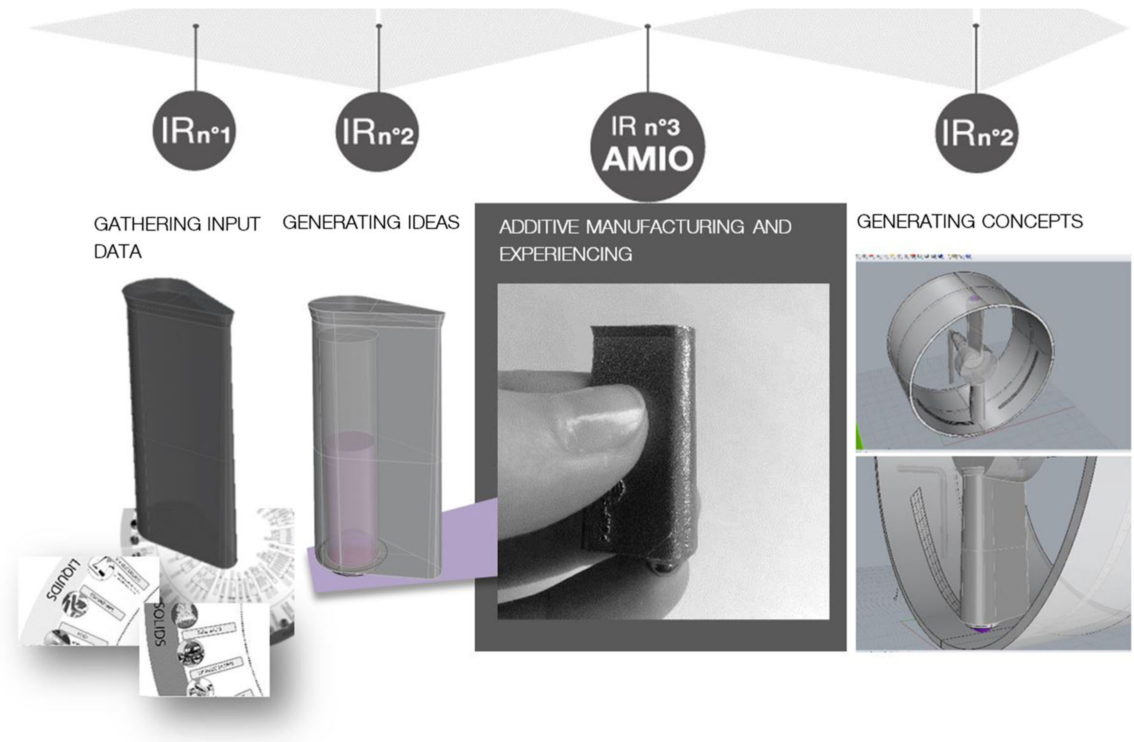

Fig. 9 Intermediate representation sequence integrating AMIO

Through sensory manipulation, AMIO are to be used in the introduction of creative sessions. For example, on Fig. 9 (IR n^{o}4), designers generated a concept of rotating blades filled in with a viscous liquid to check the alignment of the blades. They phrased that this function could be integrated in test bench turbine blades.

According to Cruz recommendations [53], AMIO are abstracted enough to not be understood as a product mock-up or a prototype. The different design stakeholders can interpret and diverge upon the objects to generate different concepts. In this sense, AMIO are open-ended objects. However, by being actually additively manufactured with the same processes and materials that could be used for the final product, AMIO also play the role of an early technical validation of the generated idea. If the idea is not realistic enough regarding AM specificities, it wont be manufacturable. Being tangible objects actually made with AM, AMIO could also contribute to give the idea more credibility to the eyes of industrial stakeholders. In this sense, AMIO are also closed objects.

6 Conclusion and future work

The main aim of this paper was to raise the need for a new kind of intermediate representation, specifically oriented to the early stages of creative design for additive manufacturing. In order to introduce a conceptual definition of AMIO we first summarized the research context: Design For Additive Manufacturing methods. It allowed us to highlight the need to focus our research on input data, design strategies and intermediate representations in order to foster the generation of creative AM concepts. This focus resulted in the proposal of a 5 stages framework of a creative approach to be integrated in the early stages of DFAM. Two case studies, A and B, allowed us to apply the first stage of our framework Features discovery, to an AM project. The results of these case studies A and B showed that conventional intermediate representations are not sufficient to support AM specificities and particularly the generation of functional and dynamic concepts with integrated functions. We introduced AMIO for that purpose.

Being part of a doctoral study, the concept of AMIO will be experimented during creative sessions with industrial stakeholders met via our industrial research context. This experimentation is expected to be the in/validation of our hypothesis that AMIO foster the generation of AM creative concepts.

References

1. Teece, D.: Profiting from technological innovation: implications for integration, collaboration, licensing and public policy. Res. Policy **15**(6), 285 (1986)
2. Henderson, R., Clark, M., Kim, B.: Architectural innovation: the reconfiguration of existing product technologies and the failure of established firms. Adm. Sci. Q. **35**, 9 (1990)

3. Segonds, F., Cohen, G., Veron, P., Peycere, J.: PLM and early stages collaboration in interactive design, a case study in the glass industry. Int. J. Interact. Des. Manuf. (IJIDeM) **10**(2), 95 (2016)
4. Laverne, F., Segonds, F., Anwer, N., Le Coq, M.: Assembly based methods to support product innovation in design for additive manufacturing: an exploratory case study. J. Mech. Des. **137**(12), 1 (2015)
5. Hague, R., Campbell, I., Dickens, P.: Implications on design of rapid manufacturing. J. Mech. Eng. Sci. **217**, 25 (2003)
6. Doubrovski, Z., Verlinden, J., Geraedts, J.: Optimal design for additive manufacturing: opportunities and challenges. In: A. (ed) ASME 2011 International Design Engineering Technical Conference and Computer and Information in Engineering Conference, vol. DETC2011-48131 (2011)
7. Schon, D.: The reflective practitioner: how professionals think in action. vol. 5126. Basic Books, (1983) ISBN-10: 0465068782
8. Pei, E., Campbell, I., Evans, M.: A taxonomic classification of visual design representations used by industrial designers and engineering designers. Des. J. **14**(1), 64 (2011)
9. Alimardani, M., Toyserkani, E., Huissoon, J.P.: A 3D dynamic numerical approach for temperature and thermal stress distributions in multilayer laser solid freeform fabrication process. Opt. Lasers Eng. **45**(12), 1115 (2007)
10. Rafi, H.K., Starr, T.L., Stucker, B.E.: A Comparison of the tensile, fatigue, and fracture behavior of Ti6Al4V and 15–5 PH stainless steel parts made by selective laser melting. Int. J. Adv. Manuf. Technol. **69**(5), 1299–1309 (2013)
11. Rias, A., Segonds, F., Bouchard, C., Abed, S.: Design For Additive Manufacturing : a creative approach. In: Marjanovic, M. Storga, N. Pavkovic, N. Bojcetic, S. Skec (eds) DESIGN 2016 Conference, May 16–19th, pp. 411–420
12. Ullman, D.: The Mechanical Design Process. Vol. 2. 4th edn. Mc Graw Hill, New York (2010)
13. Rodrigue, H., Rivette, M.: An assembly-level design for additive manufacturing methodology. In: IDMME-Virtual Concept Conference, Vol. 3 Bordeaux, France (2010)
14. Maidin, B., Campbell, I., Pei, E.: Development of a design feature database to support design for additive manufacturing. Assembl. Autom. **32**(3), 235 (2011)
15. Garcia, R., Calantone, R.: A critical look at technological innovation typology and innovativeness terminology : a literature review. J. Prod. Innov. Manag. **19**, 110 (2002)
16. Bonnardel, N.: Towards understanding and supporting creativity in design: analogies in a constrained cognitive environment. Knowl. Based Syst. **13**(7–8), 505 (2000)
17. Rosen, D.: Design for additive manufacturing: a method to explore unexplored regions of the design space. In: Proceedings of 18th Annual Solid Freeform Fabrication Symposium, pp. 402–415 (2007)
18. Maheshwaraa, U., Seepersad, C., Bourell, D.L.: Design and freeform fabrication of deployable structures with lattice skins. Rapid Prototyp. J. **13**(4), 213 (2007)
19. Chu, C., Graf, G., Rosen, D.: Design for additive manufacturing of cellular structures. Comput. Aided Des. Appl. **5**, 686 (2008)
20. Vayre, B., Vignat, F., Villeneuve, F.: Designing for additive manufacturing. In: 45th CIRP Conference on Manufacturing systems
21. Ponche, R., Hascoet, J., Kerbrat, O., Mognol, P.: A new global approach to design for additive manufacturing. Virtual Phys. Prototyp. **7**(2), 93 (2012)
22. Tang, Y., Hascoet, J., Zhao, Y.: Integration of topological and functional optimization in design for additive manufacturing. In: 12th ASME conference on engineering systems (2014)
23. Thompson, M., Moroni, G., Vaneker, T., Fadel, G., Campbell, R., Gibson, I., Bernard, A., Schulz, J., Graf, P., Ahuja, B., Martina, F.: Design for additive manufacturing: trends, opportunities, considerations and constraints. CIRP Ann. Manuf. Technol. **65**(2), 737–760 (2016)
24. Munguia, J., Riba, C., Lloveras, J.: In the search of design for rapid manufacturing strategies to solve functional and geometrical issues for small series production. In: ICED 2007 conference Paris, France (2007)
25. Boyard, N., Rivette, M., Christmann, O., Richir, S.: A design methodology for parts using additive manufacturing. In: 6th International Conference on Advanced research in Virtual and Rapid Prototyping, pp. 399–404
26. Burton, M.: Design for rapid manufacture : developping an appropriate knowledge transfer tool for industrial designers. Ph.D. Thesis (2005)
27. Burton, M.: Design for Rapid Manufacturing (DFRM) Questionnaire. SME Editor Loughborough University (2006)
28. Wohlers, A.: Additive manufacturing and 3D printing state of the industry. Annual Worldwide Progress Report (2013)
29. Pei, E., Campbell, I., Evans, M.: Building a common ground the use of design representation cards for enhancing collaboration between industrial designers and engineering designers . In: Undisciplined ! Design Research Society conference 16–19th july (2008)
30. Oxman, R.: Theory and design in the first digital age. Des. Stud. **27**, 229 (2006)
31. Sass, L., Oxman, R.: Materializing design: the implications of rapid prototyping in digital design. Des. Stud. **27**, 325 (2006)
32. Pahl, Beitz: Engineering Design. A systematic approach. Springer-Verlag, New York (2007)
33. Ansburg, P.I., Hill, K.: Creative and analytic thinkers differ in their use of attentional resources. Personal. Individ. Differ. **34**(7), 1141 (2003)
34. Goldschmidt, G., Smolkov, M.: Variances in the impact of visual stimuli on design problem solving performance. Des. Stud. **27**, 549 (2006)
35. Mougenot, C., Bouchard, C., Aoussat, A., Westerman, S.: Inspiration, images and design: an investigation of designers' information gathering strategies. J. Des. Res. **7**(4), 331 (2008)
36. Bouchard, C., Omhover, J.: Collaboration in Creative Design: Methods and Tools. Springer, New York (2016)
37. Pasman, G.: Designing with Precedents. Delft University of Technology, TU Delft (2003)
38. Bonnardel, N., Marmeche, E.: Towards Supporting evocation processes in creative design: a cognitive approach. Int. J. Hum. Comput. Stud. **63**, 422 (2005)
39. Gibson, I., Rosen, D., Stucker, B.: Design For additive manufacturing. Addit. Manuf. Technol. pp. 283–316. Springer (2010)
40. Cham, J., Pruitt, B., Cutkosky, M., Binnard, M., Weiss, L., Neplotnik, G.: Layered manufacturing with embedded components: process planning considerations. In: ASME Design Engineering Technocal Conference, pp. 1–9
41. Kataria, A., Rosen, D.: Building around inserts : methods for fabricating complex devices in stereolithography. In: ASME Design Engineering Technical Conferences, pp. 1–11
42. De Laurentis, K., Mavroidis, C., Kong, F.: Rapid fabrication of non-assembly robotic systems with embedded components. In Proceedings of the NSF Design, Service, Manufacture and Industrial Innovation Research Conference, pp. 1–30 (2003)
43. Li, X., F., P.: Embedding of fiber optic sensors in layered manufacturing. In: 11th Solid Freeform Fabrication Symposium, pp. 314–324
44. Lopes, A., Navarrete, M., Medina, F., Palmer, J., MacDonald, E., Wicker, R.: Expanding rapid prototyping for electronic systems integration of arbitrary form. In 17th Annual Solid Freeform Fabrication Symposium, Austin TX, pp. 14–16 (2006)
45. Chen, Y., Zhou, C., Lao, J.: A layerless additive manufacturing process based on CNC accumulation. Rapid prototyp. J. **17**(3), 218 (2011)

46. Isanaka, S., Liou, F.: The applications of additive manufacturing technologies in cyber-enabled manufacturing systems. In: Solid Freeform Fabrication Symposium, pp. 341–353
47. Panesar, A., Brackett, D., Ashcroft, I., Wildman, R., Hague, R.: Design optimization strategy for multifunctional 3d printing. In: Solid Freeforrm Fabrication Symposium, pp. 1179–1193
48. Wu, S., Yang, C., Hsu, W., Lin, L.: 3D-printed microelectronics for integrated circuitry and passive wireless sensors. Microsyst. Nanoeng. **1**, (2015). doi:10.1038/micronano.2015.13
49. Nadeau, J.P., Fischer, X.: Research in interactive design: virtual, interactive and integrated product design and manufacturing for industrial innovation. **3** (2011)
50. Boehm, B.: Get ready for agile methods, with care. Computer **35**(1), 64 (2002)
51. Lallemand, C., Bongard-Blanchy, K., Ocnarescu, I.: Enhancing the design process by embedding hci research into experience triggers. In: Proceedings of the ErgoIA conference pp. 41–48 (2014)
52. Boujut, J., Blanco, E.: Intermediary Objects as a Means to Foster Co-operation in Engineering Design. Comput. Support. Coop. Work **12**, 205 (2003)
53. Cruz, V., Gaudron, N.: Open-ended objects : a tool for brainstorming. In: Proceedings of the 8th ACM conference on Designing Interactive Systems, pp. 85–88 (2010)
54. De Martinoa, T., Falcidienob, B., Haingerb, S.: Design and engineering process integration through a multiple view intermediate modeller in a distributed object-oriented system environment. Comput. Aided Des. **30**(6), 437 (1998)